

LUCIAE 3.0: A new version of a computer program for Firecracker Model and rescattering in relativistic heavy-ion collisions

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Abstract: LUCIAE is a Monte Carlo program that, connected to FRITIOF, implements both the Firecracker Model (FCM), a possible mechanism for collective multi-gluon emission from the colour fields of interacting strings, and the reinteraction of the final state hadrons in relativistic heavy ion collisions. This paper includes a brief presentation of the dynamics of LUCIAE with an emphasis on the new features in this version, as well as a description of the program.

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NEW VERSION SUMMARY

Title of Program: LUCIAE version 3

Program obtainable from: taian@hptc1.ihep.ac.cn or sabh@mipsa.ciae.ac.cn or from the CPC Program Library, Queen's University of Belfast, N. Ireland

Reference in CPC to previous version: Sa Ben-Hao and Tai An, Computer Physics Commun. 90 (1995) 121 (version 2.0)

Does the new version supersede the previous one: yes

Computer for which the programme is designed: HP, ALPHA and DEC station, VAX, IBM and others with a FORTRAN 77 compiler

Computer: HP station Model 715/100; installation: Computer Center, Institute of High Energy Physics, Beijing, China

Operating system: HP-UX 10.20

Program language used: FORTRAN 77

High speed storage required: $\approx 90\text{k}$ words

No. of bits in a word: 32

Peripherals used: terminal for input, terminal or printer for output

No. of lines in combined program and test deck: about 12100

Keywords: Relativistic nucleus-nucleus collisions, Monte Carlo, collective effects, Colour Rope, effective string tension, rescattering.

Nature of the physical problem: The experiments of relativistic pA and AA collisions reveal that high energy heavy-ion collisions have some features which can not be understood by the simple superposition of independent nucleon-nucleon collisions. They indicate clearly that the collective effects are important in the relativistic pA and AA collisions. Formation of a QGP is often suggested

to be a candidate to account for some of these collective effects. Could we understand those new features in pA and AA collisions by conventional physics (on which LUCIAE is based) ? What is the limit of a model to explain the experimental data without the formation of QGP within a reasonable margin of flexibility of the model ? The Monte-Carlo generator, LUCIAE is built in an attempt to answer these questions.

Method of solution: When many strings or colour dipoles are formed in relativistic pA and AA collisions, it is natural to ask if there is some interaction among those strings close by so that both the emission of gluonic bremsstrahlung as well as the fragmentation properties can be affected by the large common energy density of the string cluster (Colour Rope). The Firecracker Model is developed to study such a collective effect. Moreover, many hadrons are produced in a small space-time volume through fragmentation of these strings, which implies that they will interact with each other and with the surrounding cold spectator matter. The rescattering effect on the distributions of the final state hadrons is also included in LUCIAE program.

Summary of revisions:

- (1) The initialization of hadrons in the space-time is modified.
- (2) Much more inelastic channels and their reverse reactions have been included in the rescattering sector.
- (3) The annihilation of \bar{p} and $\bar{\Lambda}$ in nuclear matter is taken into account.
- (4) The effect of firecracker gluons on the fragmentation of a string has been included.
- (5) The sizes of arrays have been enlarged; The values of a few parameters are adjusted and a few bugs are fixed.

Restriction of complexity of the problem: At very high energies (\sqrt{s} in the TeV range), especially for collisions of massive nuclei, certain arrays need to be expanded to accommodate the large number of particles produced.

Typical running time: Depends on the type of collision and energy. Three examples of central collisions (b=0) running on a HP Station:

$^{32}\text{S} + ^{32}\text{S}$	$p_{\text{lab}} = 200 \text{ A GeV}/c:$	$\sim 0.6 \text{ minutes/event}$
$^{207}\text{Pb} + ^{207}\text{Pb}$	$p_{\text{lab}} = 158 \text{ A GeV}/c:$	$\sim 9 \text{ minutes/event}$
$^{197}\text{Au} + ^{197}\text{Au}$	$\sqrt{s} = 200 \text{ GeV}:$	$\sim 80 \text{ minutes/event}$

LONG WRITE-UP

1 Introduction

With the advent of the BNL RHIC experiment the center of relativistic heavy-ion collisions is moving to the study of RHIC physics for Au + Au collisions at $\sqrt{s}=200$ GeV. At such a high energy heavy-ion collisions are expected to demonstrate many new features which are not covered at current AGS and CERN energies. First of all, the energy density created after the collisions is expected higher than its critical value ($1-3 \text{ GeV}/fm^3$ by lattice calculation [1]) of a phase transition from a hadronic state to a QGP state. Second, QCD hard and semi-hard processes will become important and affect the evolution of the colliding system [2].

The study of relativistic heavy-ion collisions at AGS and CERN energies, though a QGP phase transition is not unambiguously seen, demonstrates that pA and AA collisions are far more than independent superposition of binary nucleon-nucleon collisions. Many interesting collective effects occur during the collisions, some of which have thus been considered as signatures of the formation of a QGP state. In order to distinguish the real QGP signatures from “conventional” collective effects it is important to develop models based on the different non-QGP collective effects. Such models should be used in order to provide possible background for the signals of QGP formation.

FRITIOF is a string model specially developed for simulating relativistic hadron-hadron scattering by the introduction of gluon bremsstrahlung radiation as well as hard parton scattering and it has been successful in describing many experimental data at the SPS energies, which shows that the production of QCD hard and semi-hard jets plays a crucial role at such high energies[3]. On the basis of hadron-hadron interaction the FRITIOF model has also been extended to describe hadron-nucleus and nucleus-nucleus collisions in a way similar to Glauber model.

In the FRITIOF string language two strings are formed during a high energy hadron-hadron collisions. They pass by each other quickly and have little chance for further interaction. However, there are generally many excited strings formed close by each other during a relativistic heavy-ion collision. In case these strings would behave like vortex lines in a color superconducting QCD vacuum then it is conceivable that they will interact. The interacting string may form a quantum state (“Color Rope”) so that both the emission of gluonic bremsstrahlung as well as the fragmentation properties can be affected by the large common energy density. Such a scenario is described by “Firecacker model” and its application to the production of mini-jets

has been discussed in references [4].

Besides, many hadrons are produced in a small space-time volume through the string fragmentation in a relativistic heavy-ion collision, which implies that they would interact with each other and with the surrounding cold spectator matter. Such rescattering turns out to be important in the production of strange particles and anti-baryons during a collision [5].

The above collective effects, the production of firecracker gluons and rescattering of the final state hadrons, has been implemented in a computer program, LUCIAE_2.0 [6], and we have kept on developing the program ever since. The following changes have been made in the new version of the program, LUCIAE_3.0: (1) the initialization of hadrons in the space-time is modified so that uncertainty due to the initialization is minimized. (2) much more inelastic channels and their reverse reactions have been included in the rescattering sector so that the program can be used to investigate production of those strange particles like Ξ, Ω^- , for instance, through rescattering. (3) The annihilation of \bar{p} and $\bar{\Lambda}$ in nuclear matter is taken into account. (4) the effect of firecracker gluons on the fragmentation of a string has been included through the change of effective string tension in the new version of the program. (5) The sizes of arrays have been enlarged for simulating Au+Au at the RHIC energy; The values of a few parameters are adjusted and a few bugs are fixed. The physics implemented in LUCIAE_3.0 has been published in papers [7][8].

In this paper we will briefly summarize the physics on which LUCIAE program is builded with an emphasis on the new features in LUCIAE_3.0. Firecracker Model is described in Section 2. The rescattering part is described in Section 3. The description of the MC program as well as its switches and parameters will be found in Section 4.

2 Firecracker Model

When a gluon is emitted from a color dipole string with a mass M and transverse size of an order of $1/\mu$ in the cms of the string the transverse momentum k_\perp and rapidity y of the emitted gluon are restricted inside the region described in the soft radiation model[9] by

$$k_\perp \lesssim e^{-|y|} \frac{\mu}{k_\perp} M. \quad (1)$$

We note that the factor μM in eq. (1) effectively corresponds to an energy density over the region $1/\mu$. Consequently the requirement in eq. (1) means for an isolated string that the largest transverse momentum gluon fulfills $k_{\perp max} \leq \sqrt{\mu M}$.

In the Firecracker model it is assumed that in the very early stage of the collision when several (n) excited strings (energy momenta $P_{\pm j}$) are close by *it may be possible for them to emit gluons using their common total energy density* $\mu M_{tot} \equiv \mu \sqrt{\sum P_{+j} \sum P_{-j}}$.

Consequently, when it comes to heavy ion collision predictions the Firecracker model will correspond to an essential enhancement of (mini)jets in the center of phase space, which contributes to high p_t enhancement. Actually the Firecracker gluons are found so dominant in the high p_t region of phase space that the effect completely drowns both the Rutherford scattering and the “ordinary” bremsstrahlung at RHIC energy. For more details how to combine strings close by each other transversely into a colour rope and how to partition a firecracker gluon to a string, see reference [6].

The production of the firecracker gluons corresponds to a sizable transverse excitation (a “ kink ”) on a string, one of effects of which is that the existence of the firecracker gluons on a string will wrinkle the string and give a fractal structure. Such a wrinkled string has larger energy density in comparison with a string without gluon, thereby an enhanced string tension effectively [10].

The following form has been used in [8] to parametrize the relation between the effective string tension and the hard gluon jets on a string

$$\kappa_{eff} = \kappa_0(1 - \xi)^{-\alpha}, \quad (2)$$

where κ_0 is the string tension of the pure $q\bar{q}$ string, α is a parameter to be determined by experiments and ξ is calculated by

$$\xi = \frac{\ln(\frac{k_{1max}^2}{s_0})}{\ln(\frac{s}{s_0}) + \sum_{j=2}^{n-1} \ln(\frac{k_{\perp j}^2}{s_0})}, \quad (3)$$

which represents the scale that a multigluon string is deviated from a pure $q\bar{q}$ string. Here the multigluon string state has $(n-2)$ gluons, indexed in a colour connected way from the q (index 1) to the \bar{q} (index n) and $k_{\perp j}$ are the transverse momenta of the emitted gluons with $k_{\perp j}^2 \geq s_0$. The parameter $\sqrt{s_0}$ is of the order of a typical hadron mass. The parameter α in Eq.(2) and the $\sqrt{s_0}$ in Eq.(3) are determined by hh data to be about 3.5 and 0.8 GeV, respectively [8].

In the Lund string fragmentation model, the $q\bar{q}$ pairs with the quark mass m and the transverse momentum p_t are produced from the colour field by a quantum tunneling process with probability

$$\exp(\frac{-\pi m^2}{\kappa_{eff}}) \exp(\frac{-\pi p_t^2}{\kappa_{eff}}). \quad (4)$$

The above equation shows that the probability of the $s\bar{s}$ pair production with respect to a $u\bar{u}$ (or $d\bar{d}$) pair as well as the probability of a high p_t $q\bar{q}$ pair production will be enhanced in a field with larger κ_{eff} .

Assume that the width of the Gaussian transverse momentum distribution and the strangeness suppression factor of a string with effective string tension κ_{eff1} are σ_1 and λ_1 , respectively, then those quantities of a string with effective string tension κ_{eff2} can be calculated from Eq.(4), i.e.

$$\begin{aligned}\sigma_2 &= \sigma_1 \left(\frac{\kappa_{eff2}}{\kappa_{eff1}} \right)^{1/2} \\ \lambda_2 &= \lambda_1 \frac{\kappa_{eff1}}{\kappa_{eff2}}.\end{aligned}\tag{5}$$

We see that σ and λ for two string states are related by the ratio of the effective string tensions of this two string states only. It should be noted that the discussion above is also valid for the production of the diquark pairs from the string field, i.e. the production of the diquark pairs with respect to the $q\bar{q}$ pairs will be enhanced from a string with larger κ_{eff} , therefore, more baryons (or antibaryons) will be formed in the final state.

In JETSET routine which runs together with LUCIAE event generator, there are model parameters PARJ(2) (the same as λ) and PARJ(3), both of which are responsible for the s quark (diquark) suppression and related to the effective string tension. PARJ(3) is the extra suppression of strange diquark production compared to the normal suppression of strange quark pair. Besides λ and PARJ(3) there is PARJ(1), which stands for the suppression of diquark - antidiquark pair production in the color field in comparison with the quark - antiquark pair production and is related to the effective string tension as well. How these three parameters affect the multiplicity distribution of final state particles can be found in [7]. Another parameter PARJ(21) (the same as σ), which is the width of the Gaussian transverse momentum distribution of $q\bar{q}$ pairs in the string fragmentation, varies with κ_{eff} too, but it is not related to the strangeness production directly.

It has been shown in [7] that the string fragmentation by JETSET with default values of PARJ(1)=0.1, PARJ(2)=0.3 and PARJ(3)=0.4, determined from e^+e^- experiments, overestimates the yield of strange particles in the pp collision at 200 GeV/c. Thus in [8] we first retune these parameters by comparing with the pp data of strange particle production. A new set of parameters PARJ(1)=0.046, PARJ(2)=0.2 and PARJ(3)=0.3 are found for pp at 200 GeV/c. We also give a new value of 0.32 for PARJ(21) (the corresponding default value is 0.37). This set of parameters are used to calculate the particle production in pA and AA collisions at 200 GeV/c.

3 Recattering of final state hadrons

There is no space-time coordinate for the hadrons produced from strings in FRITIOF. We therefore have to initialize these particles in space-time in order to proceed the rescattering process. In LUCIAE the time origin of rescattering is chosen to be the moment when the distance between the center of the target and projectile along the beam direction is zero. It is then assumed that the particles from the string fragmentation are initially randomly placed in space inside the geometrical overlap region of the projectile and target nuclei. The “spectator” nucleons are likewise randomly distributed outside the overlap region and inside the projectile (target) nucleus and provided with a thermal motion in accordance with a Boltzman distribution. We require as always that there is a minimum distance between such spectators (“the hard intranuclear core potential”) of 0.5 fm. A formation time is given to each particle and a particle starts to scatter with others after it is “born”. The rescattering is performed in LUCIAE_3.0 in the cms frame of two colliding nuclei (however, output of rescattering is still in the Lab frame). Due to the Lorentz contraction a relativistic heavy-ion collision in the simulation looks like what is described in the Bjorken model in which the collision happens between two thin disks and a particle will be “born” at a space-time point $z = \tau \sinh y, t = \tau \cosh y$ with τ and y being the formation time and rapidity of the particle, respectively and z-axis along the beam direction.

Two particles will collide if their minimum distance d_{min} satisfies

$$d_{min} \leq \sqrt{\frac{\sigma_{tot}}{\pi}}, \quad (6)$$

where σ_{tot} is the total cross section in fm² and the minimum distance is calculated in the cms frame of the two colliding particles. If these two particles are moving towards each other at the time when both of them are “born” the minimum distance is defined as the distance perpendicular to the momentum of both particles. If the two particles are moving back-to-back the minimum distance is defined as the distance at the moment when both of them are “born”. Assuming that the hadrons move along straight - line classical trajectories between two consecutive collisions it is possible to calculate the collision time when two hadrons reach their minimum distance and order all the possible collision pairs according to the collision time sequence.

If the total and the elastic cross section satisfies

$$\frac{\sigma_{el}}{\sigma_{tot}} \geq \xi \quad (7)$$

where ξ is a random number, then the particles will be elastically scattered or else the collision will be considered as an inelastic reaction. The distribution of the

momentum transfer, t , is taken as,

$$\frac{d\sigma}{dt} \sim \exp(Bt), \quad (8)$$

where B , for an elastic scattering, depends on the masses of two scattering particles. The azimuthal angle will be isotropically distributed.

The following inelastic reactions are included in LUCIAE3.0:

$$\begin{array}{ll} \pi N \rightleftharpoons \Delta \pi & \pi N \rightleftharpoons \rho N \\ NN \rightleftharpoons \Delta N & \pi \pi \rightleftharpoons k \bar{k} \\ \pi N \rightleftharpoons k Y & \pi \bar{N} \rightleftharpoons \bar{k} \bar{Y} \\ \pi Y \rightleftharpoons k \Xi & \pi \bar{Y} \rightleftharpoons \bar{k} \bar{\Xi} \\ \bar{k} N \rightleftharpoons \pi Y & k \bar{N} \rightleftharpoons \pi \bar{Y} \\ \bar{k} Y \rightleftharpoons \pi \Xi & k \bar{Y} \rightleftharpoons \pi \bar{\Xi} \\ \bar{k} N \rightleftharpoons k \Xi & k \bar{N} \rightleftharpoons \bar{k} \bar{\Xi} \\ \pi \Xi \rightleftharpoons k \Omega^- & \pi \bar{\Xi} \rightleftharpoons \bar{k} \bar{\Omega}^- \\ k \bar{\Xi} \rightleftharpoons \pi \bar{\Omega}^- & \bar{k} \bar{\Xi} \rightleftharpoons \pi \Omega^- \\ \bar{N} N \text{ annihilation} & \\ \bar{Y} N \text{ annihilation} & \end{array}$$

where the hyperons are $Y=\Lambda$ or Σ . The relative probabilities for the different channels, e.g. in (πN) - scattering, is used to determine the outcome of the inelastic encounter. As the reactions introduced above do not make up the full inelastic cross section, the remainder is again treated as elastic encounters.

In LUCIAE_2.0 a weight factor is given to each channel in order to keep isospin conservation. In LUCIAE_3.0 we do not need such a weight factor any more since the reverse reaction of each channel (except $\bar{N}N$ and $\bar{Y}N$ annihilation) has been included. In this case the inelastic cross sections used in the program should be looked upon as isospin-averaged cross sections and the cross sections of the reverse reactions are calculated by the detailed balance.

For $\bar{N}N$ and $\bar{Y}N$ annihilation its final states are simply treated as the states of five particles through $\bar{N}N \rightarrow \rho\omega \rightarrow 5\pi$ and $\bar{Y}N \rightarrow K^*\omega \rightarrow K + 4\pi$, respectively. The cross section of $\bar{Y}N$ annihilation is taken to be 1/5 of that of $\bar{N}N$ annihilation.

4 The Description of the Program

LUCIAE3.0 is a subroutine package for simulating collective gluon emission in the Firecracker Model as well as the rescattering of the produced particles from FRITIOF in a nuclear environment. The program is written in FORTRAN 77. It should be used together with FRITIOF7.02, [11], JETSET7.4, [12], PYTHIA 5.5, [13] and ARIADNE4.02, [14]. A user should read paper [11] first before using LUCIAE3.0 if he is not familiar with using FRITIOF7.02. To run with LUCIAE3.0, FRITIOF7.02, JETSET7.4 and ARIADNE4.02 have been somewhat modified and are called FRITIOF7.02R, JETSET7.4R and ARIADNE4.02R, respectively. One important thing that a user has to keep in mind is that the dimension size of the common block COMMON/LUJETS/ (KSZJ) and COMMON/FRPARAI (KSZ1) have been extended to KSZJ=40000 and KSZ1=30. Moreover, the space-time coordinates of particles at the freeze-out time of the colliding system are now stored in array V(KSZJ,5). Those who have used FRITIOF7.02 before will find it is very easy to use FRITIOF7.02R which is linked to LUCIAE3.0 since the input and output structure of the two programs are completely the same. One simply starts with the subroutine FREVENT and ends with final state particles (after executing the Firecracker Model and rescattering) recorded in event record LUJETS.

4.1 User interface

This section contains the most essential information a user should know about the program, namely the common block FRPARA1 and LUCIDAT2 for input parameters and switch controls. The input parameters are provided with sensible default values. Several options are also included to make the program more accessible to user.

- **PARAMETER** (KSZ1=30)
COMMON/FRPARA1/KFR(KSZ1), VFR(KSZ1)

Note: KFR(1-14) and VFR(1-16) are used in FRITIOF7.02. We still list them here since some small changes have been made.

KFR(1) (D=1) Fragmentation

=0 Off.

=1 On.

KFR(2) (D=1) Multiple gluon emission (dipole radiation)

=0 Off.

=1 On.

- KFR(3)** (D=0) Event selection for collisions with a nucleus
- =0 Generate minimum bias events (all interactions recorded).
 - =1 Generate only events with all projectile nucleons participated.
 - =2 Generate only events with impact parameter between $b_{min}=VFR(1)$ and $b_{max}=VFR(2)$.
 - =3 Apply both requirements in 1 and 2.
- KFR(4)** (D=1) Fermi motion in nuclei
- =0 Neglected.
 - =1 Included.
- KFR(5)** (D=0) Nucleon-nucleon overlap function
- =0 Eikonal.
 - =1 Gaussian.
 - =2 Gray disc.
- KFR(6)** (D=2) Target Nucleus deformation
- =0 No deformation.
 - =1 Deformed target nucleus.
 - =2 Apply deformation only if the target atomic number $A \geq 108$.
- KFR(7)** (D=1) Rutherford parton scattering processes
- =0 Off.
 - =1 On. Here only the hardest RPS is used in FRITIOF.
 - =2 On. The full multiple hard scattering scenario of PYTHIA is used.
- KFR(8)** (D=1) Hard gluons cause a corner (soft gluon kink) on the string
- =0 No kink is formed.
 - =1 Gluon kink is formed.
- KFR(9)** (D=1) ‘Drowning’ of Rutherford parton scattering
- =0 Off. Accept all RPS events.
 - =-1 On. Throw away the drowned RPS event completely and replace it by a purely soft event.
 - =1 As in -1, but the transverse momentum transfer of the soft collision is superimposed by the q_T of the drowned RPS.
- KFR(10)** (D=1) SRM parameters in RPS events: $\mu_1 = \mu_0/r$, $\mu_2 = \mu_0/(1-r)$
- =0 μ remains the same as in a soft event: $\mu_1 = \mu_2 = \mu_0$.
 - =1 $r = VFR(16)$.
 - =2 r takes a uniform distribution in (0,1).
- KFR(11)** (D=4) Write out of a message when the arguments in FREVENT is changed.

- =-1** Write it out every time the change occurs.
- = n ($n \geq 0$)** The write out is limited to n times.
- KFR(12)** (D=2) Set up of the dipole cascade and string fragmentation parameters.
 - =0** No set up. The default values are used.
 - =1** Set to the values optimised by OPAL collaboration, [15]: PARA(1)=0.20, PARA(3)=1.0, PARJ(21)=0.37, PARJ(41)=0.18, PARJ(42)=0.34.
 - =2** Set to the values optimised by DELPHI collaboration: PARA(1)=0.22, PARA(3)=0.6, PARJ(21)=0.405, PARJ(41)=0.23, PARJ(42)=0.34.
- KFR(13)** (D=0) Compresses the event record to save space in LUJETS. This switch is particularly needed for heavy ion collisions at high energy where LUJETS must be compressed before it gets overfilled.
 - =0** Do not compress LUJETS.
 - =1-3** LUEDIT(KFR(13)) is called and LUJETS is compressed. Specifically, for KFR(13)=1 fragmented jets and decayed particles are removed, for KFR(13)=2 neutrinos and unknown particles are also removed, and for KFR(13)=3 neutral particles are further excluded.
 - =4** A dummy subroutine FREDITD() is provided as an interface in which a user may write his own special purpose codes to edit and compress LUJETS.
- KFR(14)** (D=0) Checked for charge and energy-momentum conservation before rescattering
 - =1** The outcome of each event will be checked.
 - =0** No checked.
- KFR(15)** (D=1) FIRECRACKER model
 - =1** On.
 - =0** Off.
- KFR(16)** (D=1) Firecracker gluon
 - =1** Accept firecracker gluons which are kinematically allowed.
 - =0** Reject all firecracker gluons. It is equivalent to KFR(15)=0.
- KFR(17)** (D=1) The ‘drowning’ of firecracker gluons by bremsstrahlung radiation.
 - =1** No drowning.
 - =0** Drowning.
- KFR(18)** (D=1) Size of firecracker cluster
 - =1** The size of firecracker cluster = VFR(17)< P_t >, with < P_t > being average transverse momentum of nucleons in the cluster.

- =0** size of firecracker cluster =VFR(18).
- KFR(19)** (D=0) Form of output, only used when KFR(21)=0
 - =1** Output in event record includes decayed strings.
 - =0** Decayed strings have been taken away in output.
- KFR(20)** (D=1) The energy dependence of the cross section of an inelastic scattering
 - =1** Constant cross section.
 - =0** Energy-dependent cross section.
- KFR(21)** (D=1) Rescattering
 - =1** On.
 - =0** Off.
- KFR(22)** (D=1) Rescattering channel
 - =1** All channels are included.
 - =0** Only some channels of interest are included. The option is put here for future use.
- KFR(23)** (D=0) Checked for charge and energy-momentum conservation after rescattering
 - =1** The outcome of each event will be checked.
 - =0** No checked.
- KFR(24)** (D=1) Treatment of spectators
 - =1** put spectators into a cluster. The cluster with the projectile spectators is placed in the (N-1)-th line of the event record with $K(N-1,2)=10000+\text{number of protons in the cluster}$ and $K(N-1,3)=\text{number of neutrons in the cluster}$. The cluster with the target spectators is placed in the (N)-th line of the event record with $K(N,2)=-10000-\text{number of protons in the cluster}$ and $K(N,3)=\text{number of neutrons in the cluster}$.
 - =0** leave spectators as individual nucleons.
- KFR(25)** (D=1) effect of effective string tension
 - =1** calculation of effective tension.
 - =0** no calculation of effective tension and JETSET default parameters are used.
- KFR(26)** (D=0) selection of a collision
 - =1** select all the collision pairs.
 - =0** only select those collision pairs with cms energy larger enough to proceed one of the inelastic reactions included.
- VFR(1)** (D=0.0 fm) Minimum impact parameter for options KFR(3)=2 or 3.

- VFR(2)** (D=0.2 fm) Maximum impact parameter for options KFR(3)=2 or 3.
- VFR(3)** (D=0.8 fm) The minimum allowable distance R_{min} between nucleons in a nucleus.
- VFR(4-5)** (D=0.2, 0.1) Dipole and quadrupole deformation coefficients for deformed target nucleus.
- VFR(6)** (D=0.01 GeV²/c²) The $\langle Q_T^2 \rangle$ for the Gaussian distribution of soft transverse momentum transfer.
- VFR(7)** (D=0.20 GeV²/c²) The $\langle Q_{2T}^2 \rangle$ for the Gaussian distribution of primordial transverse momenta on the string ends.
- VFR(8)** (D=0.75 GeV) Soft radiation coherence parameter μ_0 for projectile hadron or nucleon.
- VFR(9)** (D=0.75 GeV) Soft radiation coherence parameter μ_0 for target hadron or nucleon.
- VFR(10-11)** (D=0.0, 0.0 mb) Projectile-target nucleon total and elastic cross sections, respectively. By default, they are taken from the parameterization of Block and Cahn, [16] (MSTP(31)=5 in PYTHIA). The meson-nucleon cross sections are obtained simply by scaling down the Block-Cahn fit. The scale factor is $(2/3 - a/\sqrt{s})$, where $a = 1.13$ GeV for pions and $a = 3.27$ GeV for kaons are chosen to reproduce the low energy experimental data. For all the other baryons, it is treated as a pion if it is a meson and it is treated as a proton if it is a baryon. User may override the default by setting VFR(17-18) to positive values. However, the user assigned cross sections will only affect the N-N interaction probability in nucleus collisions. The probability for Rutherford parton scattering is not affected.
- VFR(12)** (D=1.0 GeV/c) The q_{Tmin} for Rutherford parton scattering.
- VFR(13-15)** (D=1/6, 1/3, 1/2) The probabilities for assigning various spins and flavours to the diquark end of the string. For example in a proton, VFR(13-15) are the probabilities of finding a ud diquark of spin 1, a uu diquark of spin 1, and a ud diquark of spin 0, respectively.
- VFR(16)** (D=0.5) The fraction r in option KFR(10)=1.
- VFR(17)** (D=1.0) The size of firecracker cluster with respect to the average transverse momentum of nucleons in the cluster. See also KFR(18).
- VFR(18)** (D=0.35GeV/c) The size of firecracker cluster when KFR(18)=0.
- VFR(19)** (D=6.5GeV) Minimal CMS energy for starting FIRECRACKER model.
- VFR(20)** (D=0.35mb) Cross section for $\pi + N \rightarrow K + Y$ when KFR(20)=1.
- VFR(21)** (D=3.0mb) Cross section for $\pi + N \rightarrow \Delta + \pi$ when KFR(20)=1.
- VFR(22)** (D=1.0mb) Cross section for $\pi + N \rightarrow \rho + N$ when KFR(20)=1.
- VFR(23)** (D=6.0mb) Cross section for $N + N \rightarrow \Delta + N$ when KFR(20)=1.

VFR(24) (D=3.5) the parameter α for calculating the effective string tension.
VFR(25) (D=0.8) the parameter m_0 for calculating the effective string tension.

- COMMON/LUCIDAT2/KFMAXT,PARAM(20),WEIGH(400)

KFMAXT (D=32) The maximum number of particle species included in rescattering.

PARAM(1) (D=40.0mb) The total cross-section of reaction NN .

PARAM(2) (D=25.0mb) The total cross-section of reaction πN .

PARAM(3) (D=35.0mb) The total cross-section of reaction KN .

PARAM(4) (D=10.0mb) The total cross-section of reaction $\pi\pi$.

PARAM(5) (D=3.0mb) The cross section of $\pi + \pi \rightarrow \bar{K} + K$.

PARAM(6) (D=0.85) The ratio of inelastic cross-section to total cross-section.

PARAM(7) (D=0.5fm) The formation time of a hadron at its rest-frame.

PARAM(8) (D=0.01fm) The minimal step of time elapsing.

PARAM(9) (D=0.1) The accuracy of four-momentum conservation when sampling spectator nucleons.

PARAM(10) (D=2.0) The size of effective rescattering region is $\text{PARAM}(10)R_t$ with R_t being the radius of target.

PARAM(11) (D=0.16/fm³) The nucleon density of nucleus.

PARAM(12) (D=0.01 GeV²/c²) $< P_t^2 >$ for the Gaussian distribution of spectator nucleons.

PARAM(13) (D=28.0) $\bar{N} N$ annihilation cross section.

PARAM(14) (D=5.6) $\bar{\Lambda} N$ annihilation cross section.

WEIGH(1)-WEIGH(400) not used.

4.2 Other common blocks

The following common blocks are used for transmitting data internally. While they can be accessed to read out information, they should never be used to input data.

- COMMON/FCRSOUT/ MCL(10),RCL(20),INEL(400),NST(2,150),ACL(2,150)

MCL(1): The number of cluster from projectile.

- MCL(2):** The number of cluster from target.
- MCL(3):** The number of accepted firecracker gluons.
- MCL(4):** The number of the initial collision pairs of rescattering.
- RCL(1):** JETSET parameter PARJ(1) averaged over all strings when KFR(25)=1.
- RCL(2):** JETSET parameter PARJ(2) averaged over all strings when KFR(25)=1.
- RCL(3):** JETSET parameter PARJ(3) averaged over all strings when KFR(25)=1.
- RCL(4):** JETSET parameter PARJ(21) averaged over all strings when KFR(25)=1.
- RCL(5):** number of elastic rescatterings taken place in aggregate.
- RCL(6):** number of inelastic rescatterings taken place in aggregate.
- RCL(7):** number of inelastic rescattering that is treated as an elastic scattering in aggregate because the corresponding inelastic channel is not included in the program.
- RCL(8):** number of total rescattering taken place in aggregate.
- INEL(I):** The total number that I-th inelastic channel takes place in aggregate. Order can be found in the subroutine “coinel” in the source code.
- NST(L,J):** The number of strings in J-th cluster. L=1,2 - index to label projectile (L=1) and target (L=2).
- ACL(L,J):** The invariant mass of J-th cluster. Index L has the same meaning as in NST(L,J) .

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Appendix A

The following is a sample main program.

```
C..This program generates a few sample LUCIAE events, and then does
C..histogram for negatively charged particle multiplicity distribution
C..in O+Au collision at 200 GeV/nucleon lab energy.
C..This routine, loaded together with (FRITIOF_7.02R, ARIADNE_4.02R,
C..PYTHIA5.5 and JETSET7.4R) can be used to test the installation of programs.
C-----
```

```
      PARAMETER (KSZJ=40000,KSZ1=30)
C...    **** Be sure to check that all the KSZJ's in MAIN, Fritiof,
C...      Jetset and Pythia are identically set      *****
      COMMON/FRPARA1/KFR(KSZ1),VFR(KSZ1)
      COMMON/FRINTNO/PLIO(2,4),AOP(KSZ1),IOP(KSZ1),NFR(KSZ1)
      COMMON/LUDAT1/MSTU(200),PARU(200),MSTJ(200),PARJ(200)
      COMMON/LUJETS/N,K(KSZJ,5),P(KSZJ,5),V(KSZJ,5)
      COMMON/LUDAT3/MDCY(500,3),MDME(2000,2),BRAT(2000),KFDP(2000,5)
      DIMENSION MP(0:300)

C...Open a file to take the write out of the program:
      MSTU(11) = 20
      OPEN(MSTU(11),FILE='test.out',STATUS='unknown')

C::::::::::Multiplicity distribution for O+AU collision at 200 GeV ::::::::::

C...Forbid the decays of Lambda and K_S0:
      MDCY(LUCOMP(3122),1) = 0
      MDCY(LUCOMP(310),1) = 0

C...Book spaces for the histogram (or use a histogram package):
      DO 50 J=0,300
50    MP(J) = 0

C...Test 50 events (of course a lot more events are needed realistically):
      NEVENT=50
      NTRIG = 0
      DO 100 I=1, NEVENT

      CALL FREVENT('FIXT','O','AU',200.)

C...Output the event using JETSET routine LULIST:
      IF(I.LE.3) CALL LULIST(1)

C...Edit the event record, remove partons or decayed particles:
      CALL LUEDIT(1)
```

```

C...Assume a trigger requiring that the energy in the forward cone
C...(theta < 0.3 degree) must be less than 60% of the total beam energy.
C...Also find out the number of negatively charged particles:
      IQTRIG = 0
      EFWD = 0.
      N_ = 0
      DO 70 J=1, N
      THETA = PLU(J,14)
C... (PLU is a JETSET function. Please refer to the JETSET manual.)
      IF(THETA.LT.0.3) EFWD = EFWD+PLU(J,4)

C...Count the negative particles. Spectator nucleons, which have codes
C...ABS(K(J,2))=10000+N_proton, must be excluded:
      IF(ABS(K(J,2)).LT.10000) THEN
        IF(PLU(J,6).LT.0.) N_ = N_+1
      ENDIF
70    CONTINUE

      EBEAM = 200.*IOP(3)
      IF(EFWD.LT.0.6*EBEAM) IQTRIG = 1

C...Do histogram:
      IF(IQTRIG.EQ.1) THEN
        NTRIG = NTRIG+1
        MP(N_) = MP(N_)+1
      ENDIF

100  CONTINUE

C...Output the histogram data:
      WRITE(MSTU(11),500) NEVENT, NTRIG
      DO 200 J=0,300
200  WRITE(MSTU(11),*) J, FLOAT(MP(J))/FLOAT(NTRIG)
500  FORMAT(X,'Number of events:',I4,2x,'Triggered events:',I4)

C...Write out the values of the parameters and some statistics:
      CALL FRVALUE(0)

      CLOSE (MSTU(11))
      END

```

References

- [1] J. Cleymans et al. Phys. Rep. 130 (1986) 217.
- [2] L. Xiong and E. Shuryak, Phys. Rev. C49 (1994) 2203; K. Geiger and B. Muller, Nucl. Phys. B369 (1992) 600; T. Biró et al, Phys. Rev. C48 (1993) 1275.
- [3] B. Andersson, G. Gustafson and H. Pi, Z. Phys. C57 (1993) 485.
- [4] B. Andersson, Phys. Lett. B256 (1991) 337; B. Andersson and A. Tai, Z. Phys., C71, (1996) 155.
- [5] Sa Ben-Hao, Tai An, and Lu Zhong-Dao, Phys. Rev., C52 (1995) 2069; B. Andersson, An Tai and Ben-Hao Sa, Z. Phys., C70 (1996) 499.
- [6] Sa Ben-Hao and Tai An, Computer Physics Commun. 90 (1995) 121.
- [7] Sa Ben-Hao and Tai An, Phys. Rev., C55 (1997) 2010; Phys. Lett. B399 (1997) 29.
- [8] Tai An and Sa Ben-Hao, Phys. Lett. B409 (1997) 393; Phys. Rev., C57 (1998) 261.
- [9] B. Andersson et al, Z. Phys. C43 (1989) 625.
- [10] T. Sjöstrand's lecture note in Lund.
- [11] H. Pi, Computer Physics Commun. 71 (1992) 173.
- [12] T. Sjöstrand, "A Manual to The Lund Monte Carlo for Jet Fragmentation and e^+e^- Physics: JETSET version 7.3", available upon request to the author.
- [13] H. -U. Bengtsson and T. Sjöstrand, Computer. Physics. Commun. 46 (1987) 43.
An updated version of this paper, "A Manual to The Lund Monte Carlo for Hadronic Processes: PYTHIA version 5.5", is available upon request to the authors.
- [14] L. Lönnblad, "ARIADNE version 4, A Program for Simulation of QCD Cascades implementing the Colour Dipole Model", DESY 92-046.
- [15] M. Z. Akrawy et al, Z. Phys. C47 (1990) 505.
- [16] M. M. Block and R. N. Cahn, in *Physics Simulations at High Energy*, edited by V. Barger, T. Gottschalk and F. Halzen (World Scientific, Singapore, 1987), p. 89.